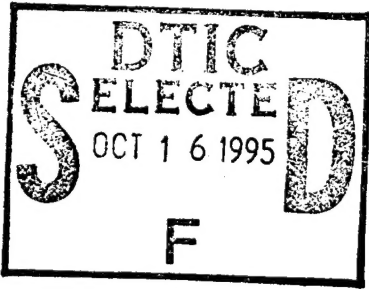


PROGRESS REPORT

CONTRACT N00014-95-0128, PHASE I SBIR PROGRAM

"GIANT MAGNETORESISTIVE SENSORS"



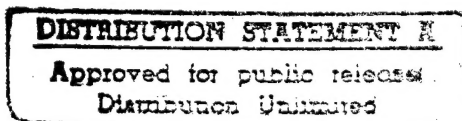
TO

OFFICE OF NAVAL RESEARCH

FROM

JAMES M. DAUGHTON, PRINCIPAL INVESTIGATOR

MAY 1, 1995



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**PROGRESS REPORT, PHASE I SBIR PROGRAM
GIANT MAGNETORESISTIVE SENSORS
CONTRACT N00014-95-0128**

J. M. DAUGHTON, PRINCIPAL INVESTIGATOR

This is the first quarterly report under contract N00014-95-0128, which calls for a progress report to be delivered to ONR by May 3, 1995. The report is organized as follows: I. Program Overview and Objectives of the Program, II. Progress in the Reporting Period, III. Anticipated Results for the Next Period and for the Program.

I. Program Overview and Objectives of the Program

The program overview as taken from the project summary in the proposal is as follows:

"Giant Magnetoresistive Ratio (GMR) materials will be used to model, specify, and design monolithic magnetic field sensors for detecting motion of ferromagnetic bodies and low magnetic fields. Magnetic fields in the 10^{-8} to 10 gauss are of primary interest. Three kinds of GMR multilayers will be examined: 1) antiferromagnetic-coupled multilayers, 2) spin-valve or symmetrical spin-valve multilayers which use "pinning", and 3) unpinned magnetic layers sandwiching a conducting interlayer. Four sensor configurations will be examined: 1) shield/flux concentrators with no bias, 2) an on-chip permanent magnet bias, 3) an on-chip integrated electromagnetic circuit bias, and 4) a self-biasing technique. In Phase I modeling based on materials measurements will be used to select the best GMR multilayer structure and the best sensor configuration. Also in Phase I, development models of this sensor with discrete signal conditioning electronics will be characterized by at least one government laboratory and by two companies who have expressed interest in the military applications of these sensors. In Phase II monolithic prototype sensors with integrated circuit underlayers will be designed, fabricated, and characterized in collaboration with commercial and government laboratories in anticipation of transfer to production."

The specific objectives from the proposal are:

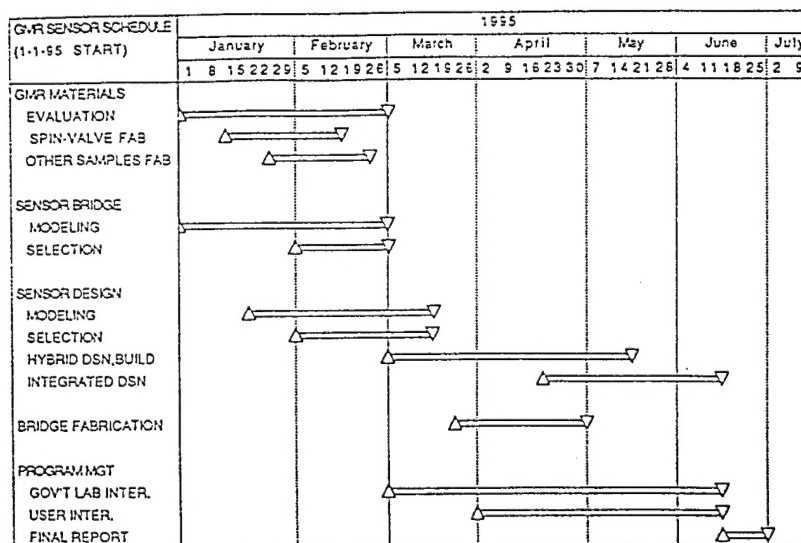
- Characterize the electrical, magnetic, and noise properties of the following GMR multilayers:
 - 1) antiferromagnetic-coupled multilayers

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- 2) spin-valve or symmetrical spin-valve multilayers which use "pinning"
 - 3) unpinned magnetic layers sandwiching a conducting interlayer
- These characteristics will be used to model the performance for various fields in the range of 10^{-8} to 10 gauss for the following GMR bridge configurations with:
 - 1) no bias
 - 2) an on-chip permanent magnet bias
 - 3) an on-chip integrated electro-magnetic circuit bias
 - 4) a self-biasing technique.
 - Based on this modeling and interactions with government labs and prospective users, an optimized magnetoresistance sensor (using the best combination of GMR multilayers and sensor configurations) will be designed.
 - Hybrid sensors/conditioning electronics assemblies will be fabricated by NVE and evaluated by NVE, at least one government laboratory and at least one other prospective user.
 - A monolithic version of this sensor with underlying integrated circuits will be designed.

II. Progress in the Reporting Period

SUMMARY - Work is progressing relatively smoothly along the directions set out in the program plan. We are about 1/4 finished through the program plan which is depicted below:



Program Schedule

Note the anticipated start date in the proposed program plan was January 1, 1995 with a planned completion planned of July 1, but the contract date was actually April 6, 1995, and the actual program completion date is October 3. The updated schedule is thus a few days more than 3 months delayed from the proposed schedule.

We have completed the initial GMR material analysis and testing of 1) antiferromagnetic-coupled multilayers, 2) spin valve and symmetrical spin valve, and 3) unpinned magnetic sandwiches for suitability in GMR sensors for the field ranges of interest. Measurements included magneto-resistance, saturation field, sheet ρ , thermal coefficients of resistivity and delta resistivity, and a significant amount of noise testing. The findings are that noise is the chief materials/device limitation for achieving sensors in the micro-Gauss and lower sensitivity ranges, and that several GMR materials are potentially usable for the 10^{-5} to 10 Gauss (Oe) range.

We have progressed in the evaluation of sensor configurations as well. We have tested the concept of 1) shield/flux concentrators with no bias down to the micro-Gauss level and have concluded that flux concentrators with large length to gap ratios do indeed give very high field magnification (up to $\times 100$), and surprisingly do not add significantly to the noise when compared to the electronic noise from the GMR materials. We have not as yet started on the 2) on-chip permanent magnet bias configuration, but have procured very tiny ferrite magnets which are small enough to attach to the sensor I.C., and we will begin working on a permanent magnet version in the next month. The configuration 3) an on-chip integrated electro-magnetic circuit bias, is in processing, and the initial test results will be available next month. The configuration 4) a self-biasing technique has been analyzed sufficiently under another program to decide its merits, and an additional self-biasing technique has been discovered in $0.2\ \mu\text{m}$ wide multilayer structures which will be investigated further. The noise work has shown that the layout of metal contacts, line widths, turnarounds in meandering resistors, and magnetic overlaps of contacts can all have an effect on noise, and optimization of these will require more work.

Work on sensor design has just been started, with the major consideration being to develop the best circuit strategy to cope with noise at low fields. It is likely that some chopping scheme will have to be used to eliminate $1/f$ noise from the GMR materials. An initial sensor design will be selected by the next reporting date.

GMR MATERIALS - GMR materials which have been fabricated at NVE prior to the start of this program include: antiferromagnetic coupled multilayers (and sandwiches), spin valves and symmetrical spin valves, and unpinned sandwiches of several types. Characteristics of these materials have been compared for applications in this program. Major considerations include: magnetoresistance, saturation field, linearity and hysteresis, TCR and changes in magnetoresistance with temperature, sheet resistivity, and noise.

For purposes of selecting a GMR material for this program, the TCR and changes in magnetoresistance with temperature, sheet resistivity are satisfactory and approximately equal for each of the materials except for the spin valve and symmetric spin valve. The TCR is about 1500 ppm/degree C. The change in percent magnetoresistance with temperature is about 2000 ppm/degree C. Both temperature variations can be easily compensated by circuit techniques. In the case of most spin valves and symmetric spin valves, there is a problem with high temperature operation because of the loss of coercivity of the hard layer with temperature, resulting in very sharp reductions in GMR from room temperature to 150 degrees C. Sheet resistivity is between 10 and 20 Ω /square for all of the structures. Thus, the critical selection criteria are: magnetoresistance, saturation field, linearity and hysteresis, and noise, with the spin valve and symmetric spin valve having an additional constraint of relatively low operating temperatures (say below 100 degrees C).

When saturation fields and magnetoresistance are considered together, the available signal per magnetic field can be inferred for low field (the most critical) applications. In a bridge configuration the maximum output signal voltage is roughly $\frac{1}{2} * V * \text{GMR}$ or $V * \text{GMR}$, depending on the bridge scheme used, where V is the supply voltage, and the output for signals below the saturation field is roughly $\frac{1}{2} * V * \text{GMR} * (\text{Heff}/\text{Hsat})$ or $V * \text{GMR} * (\text{Heff}/\text{Hsat})$, where Heff is the effective field at the magnetoresistor and Hsat is the saturation field, and a linear variation with field is assumed. By using a shield/flux concentrator, the effective field can be much higher than the ambient field, and we have demonstrated a 100 times factor. The low field response can then be approximated. If a micro-Gauss (10^{-6} Oe) field is applied to a sensor bridge with a 100:1 field multiplication and a source voltage of 5 Volts, and if a 15% GMR multilayer with a 200 Oe saturation field, the output from the bridge would be approximately $5 * 0.15 * (10^{-4}/200)$ or 375 nV.

The output with 10^{-8} Gauss field would be only 3.75 nV, which is marginally detectable if the noise is low enough.

The Johnson (fundamental limit) noise from a 1000 Ω resistor at room temperature is $1.26 \times 10^{-10} \cdot (1000 \cdot \Delta f)^{1/2}$, where Δf is the band width of the system. With a 10 Hertz bandwidth, the noise would be 12.6 nV. For the signal at 10^{-6} Oe field, this would be a signal to noise ratio of 37.5/12.6 or almost 3:1, which would be marginally adequate in many cases. The noise would be much larger than the signal at 10^{-8} Oe. To make matters worse, the actual noise in GMR materials is far above the Johnson noise levels. Below 10^{-6} Oe fields, a higher sensitivity is required to get an adequate signal. At 10^{-8} Oe, both much higher sensitivity and a noise approaching the Johnson noise level are required. *The largest program challenge will be to achieve reasonable signal to noise ratios at the low end of the field range.*

In the first month of this program, we worked with Honeywell to measure noise in several types of GMR materials, and we explored different resistor designs. In addition, we learned how to make the tests ourselves, which will reduce cost to the program in the future and improve the pace of development. We now have our own spectrum analyzer and small chambers which minimize external fields. In our initial test we have learned the following:

- The noise in GMR resistors we tested was higher than the Johnson noise level by a factor of 15 to 1000.
- The multilayers had the lowest noise and the uncoupled sandwiches the highest. Spin valves were in the middle.
- The design of the contacts is critical, along with the length of magnetic material past the contact (it should be long) and the turnarounds in a meandering resistor (they should be covered with metal).
- Wider resistors have less noise for the same resistance values.
- The noise is current dependent
- Clamping magnetoresistors with large magnetic fields does not eliminate the high noise levels (noise improves about a factor of 2).

We are still in the initial stages of determining noise sources in the material and have not yet designed resistors using all of the techniques we have learned to date. This will be done in the next month. We are convinced that noise levels at 10 or less times the Johnson noise is achievable.

Hysteresis and linearity are satisfactory for GMR multilayer and spin valve structures at higher field levels. At low field levels, we have found the even materials with a lot of hysteresis can be used to get a linear output with little hysteresis. Consider a bridge with an unpinned sandwich with considerable hysteresis. Figure 1 shows the output from the bridge as a function of external field. This characteristic mirrors the hysteresis seen in the individual resistors making up the bridge.

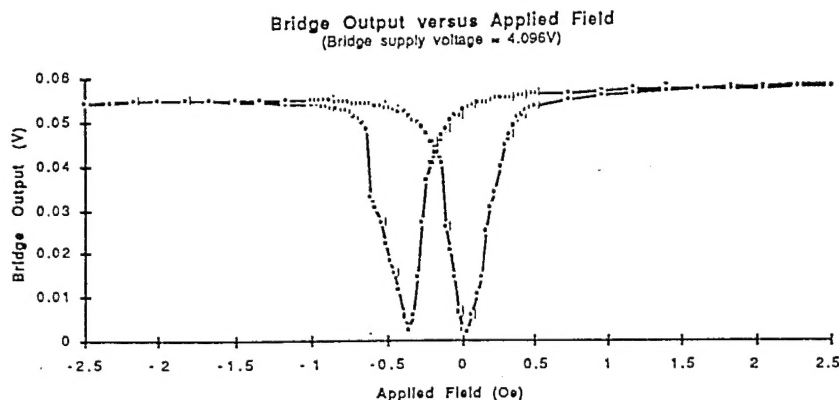


Figure 1. Transfer Characteristic of a Bridge with Hysteresis

Figure 2 shows the output signal from the bridge as a function of field in the 1 to 42 nT range (10 μ Gauss to 420 μ Gauss). Note that the linearity is good and the hysteresis is small. We therefore believe that linearity can be achieved for very small fields with any GMR material, and for larger fields either multilayers or spin valves would be satisfactory.

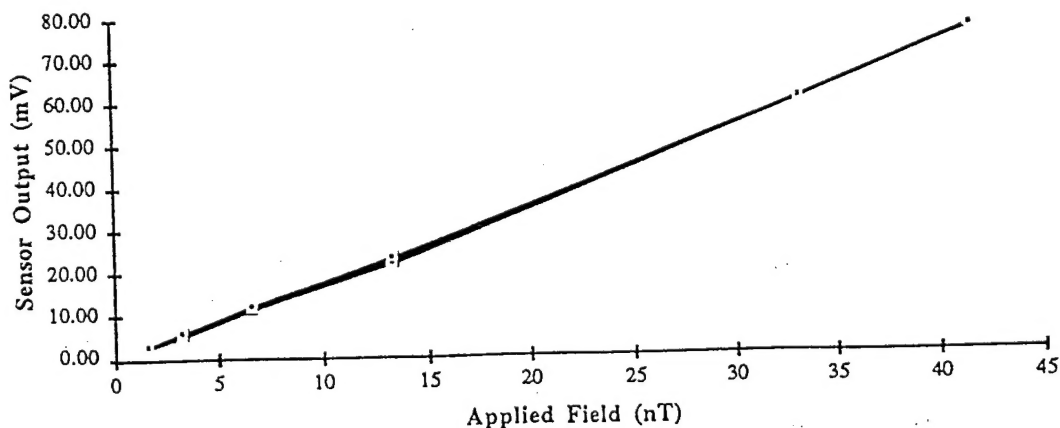


Figure 2. Low Signal Output from Sensor in Figure 1.

A GMR device which could have very high sensitivity is a tunneling device. In the past 6 months, workers in both the US and in Japan have produced devices which work on a tunneling principle. Two magnetic materials separated by a thin dielectric demonstrate a change in tunneling current when the magnetic state is changed. In theory, this device could give a change in tunneling current of 20 % with only a fraction of an Oe field, a potential improvement of a factor of 100. This program is not large enough to fund tunneling work, but we are funded under another program to explore this area. If GMR tunneling develops in time for this program, we will consider using it.

SENSOR BRIDGE - As mentioned earlier, we are considering several options for bridge designs. We have found that high field multiplication can be achieved with flux concentration without introducing noise and hysteresis, at least in the 10^{-5} Oe range. A biasing technique can give a factor of two improvement in output compared to the shield technique, because both pairs of magnetoresistors change values with field instead of only one set. In view of the higher signal required, we have to consider that factor of 2 signal too valuable to lose. The three kinds of biasing techniques proposed were: using a permanent magnet, using an electromagnetic circuit, and a self biasing technique.

The electromagnetic circuit is the most flexible of the three techniques, and if it can be fabricated, is the bridge scheme of choice (please see page 10 of the proposal for a description). Flux multiplication comes as part of this approach, and the length to gap ratios should be about the same as for the flux concentrator/shield scheme. It is especially powerful when the total sensor requirements are considered. The bias field can be reversed without introducing any noise into the sensing circuit, and this could be a very effective way to reduce $1/f$ noise. The output would reverse polarity when the bias is reversed, and the sensing scheme could invert the output (after amplification). The low frequency noise would not reverse in this time interval.

In addition, a feedback scheme could be used whereby the field current is used to maintain a constant bridge offset level, and a "threshold" type of material could be used. This could be, for example, a GMR material with a sharp threshold where the resistance changes very rapidly with field, such as in a square B-H loop material. The feedback current is then a measure of the applied field.

The permanent magnet technique is more difficult to implement if field multiplication is to be retained. It does have the

advantage of being lower power, and it may be easier to fabricate than the electromagnetic circuit technique.

The self biasing technique can be used in an electromagnetic circuit which retains field multiplication, but does not require a bias field. Edge spins in a narrow stripe have been shown to give 5% GMR with less than 10 Oe field, which is a very good sensitivity. If noise is not a problem, this could be a very promising direction. A potential problem with this approach is that it can be "upset" with large external fields. Another type of self-biasing scheme would be much less prone to upset was discovered recently on another program. When a GMR multilayer was etched into a very narrow stripe, the resistor characteristic with magnetic field appeared as in Figure 3. We have not completed the analysis of this structure, but with proper design and if the noise is low, this type of resistor could make a very good sensor element.

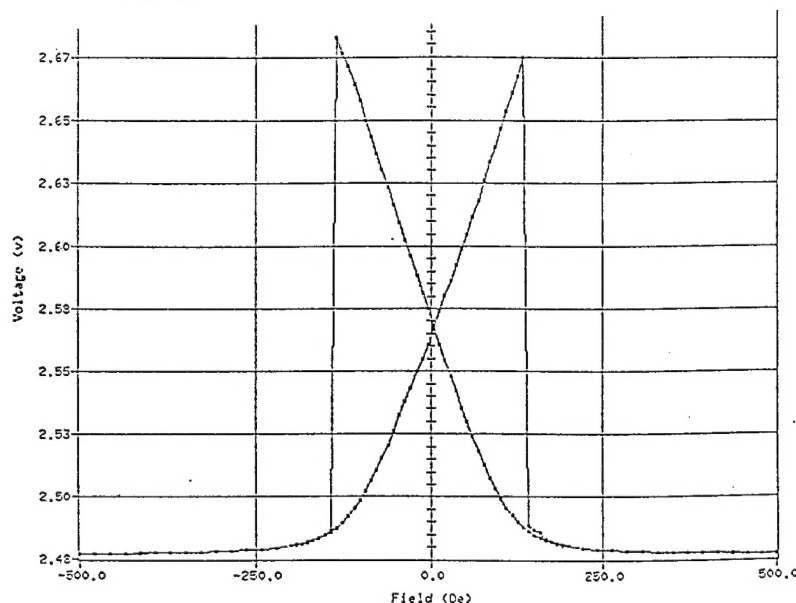


Figure 3. 0.2 μm GMR Multilayer Stripe Resistance with Field

SENSOR DESIGN - The sensor design will combine the magnetic sensor bridge with the electronics. Naturally the bridge and electronic designs are interwoven. We have just started to consider the electronics design, and should have recommendations for the preferred approach for the next report. Because the initial demonstration model is to be a hybrid assembly, we will consider only off-the-shelf components. As mentioned in the previous section, the current favorite approach would be to use a chopped bias current in an electromagnetic biasing circuit, and try to

eliminate $1/f$ noise by chopping the amplified sense signal (with inversion) and adding.

III. Anticipated Results for the Next Period and for the Program

Work in the next period will be concentrated on selection of the best GMR material, the best sensor bridge technique, and the best sensor design. Based on these selections, we will begin to design, assemble, and test a hybrid sensor without the optimum sensor bridge. We will also select a government lab to work with on evaluation of the sensor.

Noise measurements with improved resistor designs is one key determinant of what GMR material should be selected.

Determining if the electromagnetic circuit can be fabricated successfully, and if so, determining if its properties are as good as we expect them to be is another key milestone to be met in the next period.

Overall the program is in relatively good shape for both schedule and cost (although as a fixed price program, this is not a high level concern). The greatest challenge is performance of the sensors at very low fields in light of the noise measurements we have now. Fortunately, we are now able to measure noise ourselves thanks to the help given us by Honeywell, and we can perform quick-turn experiments to help make rapid progress. At this point we anticipate a totally successful on-time program provided noise doesn't prove to be too large an obstacle.

The following appendix describes the fabrication of the GMR samples which we used to characterize the magnetic, electrical, and noise characteristics of the GMR materials.

APPENDIX

TO

PROGRESS REPORT

"GIANT MAGNETORESISTIVE SENSORS"

GMR MATERIALS AND WAFER PROCESSING

J. HAUGEN, NVE

MAY 1, 1995

GMR Materials and Wafer Processing

NVE processed a total of 5 wafers for evaluation. The 5 wafers each had different GMR materials deposited on them. For the GMR depositions, NVE uses a Perkin Elmer 2400 sputter system. The system has been modified for the purposes of enhancing GMR results. Some of the modifications include 1) a re-machined top plate so 4 targets can be utilized in the deposition 2) computer control of the deposition sequence 3) an external magnet configuration for setting an easy axis 4) a gas control system which includes downstream pressure control 5) a Residual Gas Analyzer (RGA). All GMR wafers are built on 2000 Å of LPCVD silicon nitride. The standard GMR deposition process is as follows:

1. Transfer the wafer into the load lock.
2. The wafer is automatically transferred to the process chamber.
3. The chamber is pumped to below 2.5×10^{-7} Torr.
4. The RGA is checked to insure process chamber integrity.
5. Argon is turned on. Pressure is at 5 mTorr.
6. All targets are burned for 2 minutes at 350 watts.
7. The pressure is changed to 20 mTorr.
8. The actual GMR deposition takes place at 100 watts.
9. The wafer is unloaded at completion.

The wafers constructed for this program are listed in the following table.

| <u>Wafer ID</u> | <u>GMR type</u> | <u>Construction (bottom layer listed first)</u> |
|-----------------|----------------------|---|
| 44311_8 | multilayer | NiFeCo 40Å/CoFe 15Å/CuAgAu 17.5Å/CoFe 15Å/NiFeCo 20Å/CoFe 15Å/CuAgAu 17.5Å/CoFe 15Å/NiFeCo 20Å/CoFe 15Å/CuAgAu 17.5Å/CoFe 15Å/NiFeCo 40Å/Ta 150 Å |
| 5055_3 | spin valve | Co 40Å/Cu 30Å/Co 40Å/NiO 500Å |
| 5056_3 | symmetric spin valve | NiO 500Å/Co 40Å/Cu 30Å/Co 40Å/Cu 30Å/Co 40Å/NiO 500Å |
| 5078_5 | sandwich | NiFeCo 40Å/CoFe 15Å/Cu 45Å/CoFe 15Å/NiFeCo 40Å/Ta 200Å |
| 50310_1 | sandwich | NiFeCo 40Å/CoFe 15Å/Cu 45Å/CoFe 15Å/NiFeCo 40Å/Ta 200Å |

Wafer Processing

After the GMR depositions are done, the wafers are processed to allow for subsequent measurement and test of the GMR materials. The top 4 wafers listed above went through a simple 3 layer process while 50310_1 saw the addition of plated permalloy shields as part of the process. The first step after GMR deposition is Etch Stop deposition. The etch stop nitride will be used as a mask during the ion mill of the GMR material. The first photo layer defines the shape of the GMR resistors. After photo, the nitride is etched and the resist is stripped. At this point, the wafers are ion milled and the GMR resistors are in place. Another nitride dep is now done to passivate the GMR resistors. Window photo and etch are done to open up contacts to the GMR material. Aluminum/ 2 % Copper is sputtered onto the wafers to form the interconnect. After the Aluminum is patterned, the wafers are ready for electrical test. An example of the patterns in place for testing is Figure 1.

Wafer 50310_1 went on for further processing. A thick layer of nitride was deposited after the metal layer was defined. The wafer is now ready for the permalloy plating process. A thin plating seed layer of NiFeCo is sputtered. The wafer is then patterned with very thick photoresist. The actual plating will occur in the resist openings. First, gold is plated to a thickness of 3 microns. The gold acts as an adhesion promoter and a stress reliever for the plated permalloy. The wafer is then put through photomasking again. Finally, the permalloy is plated through the resist openings to thickness of 12.5 microns. See Figure 2 for a complete summary of the wafer processes used as part of this program.

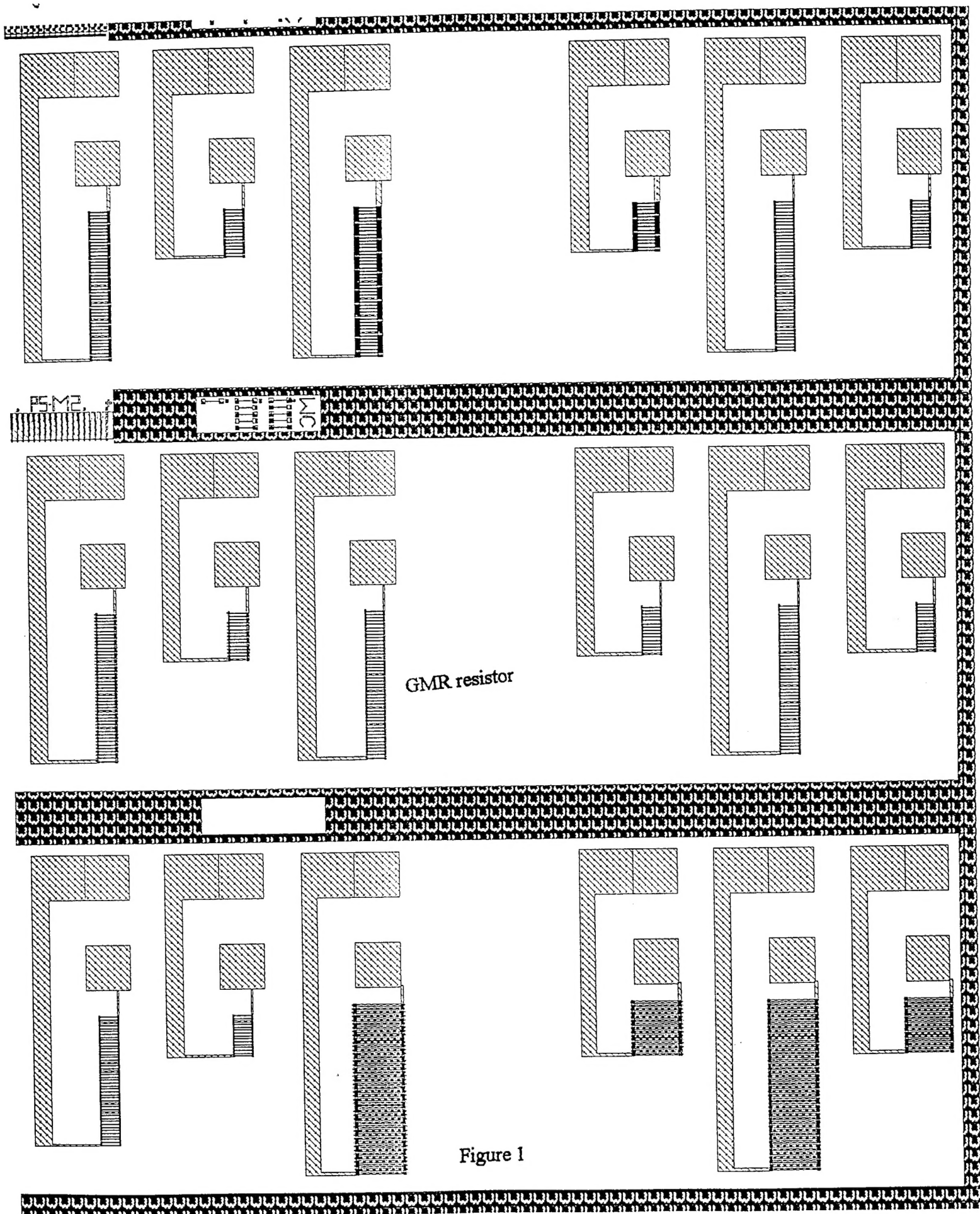


Figure 1

NVE Bridge Sensor Process Flow

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| STEP | Material | Target | Process Tool |
|---------------------|------------|--------------|-------------------|
| Magnetic Layers Dep | GMR | 400 Ang. | PE 2400 |
| Etch Stop Dep | CrSi/Si3N4 | 100 A/1000 A | MRC 8667 |
| GMR Photo | | 2 micron | GCA Stepper |
| GMR Nitride Etch | | | Drytek RIE |
| GMR Etch | | | Ion mill |
| Window Dep | Si3N4 | 1500 A | MRC 8667 |
| Window Photo | | 2 micron | GCA Stepper |
| Window Etch | | | Drytek RIE |
| M1 Dep | Al/ 2% Cu | 5000 A | MRC 8667 |
| M1 Photo | | | GCA Stepper |
| M1 Etch | | | Wet Etch |
| Via Dep | Si3N4 | 10000 A | PECVD |
| Plating Seed Dep | NiFeCo | | PE 2400 |
| Shield 1 Photo | | | GCA Stepper |
| Au Plating | Au | 3 microns | Electroplate bath |
| Shield 2 Photo | | | GCA Stepper |
| Permalloy Plating | NiFe | 12.5 micron | Electroplate bath |
| Seed Layer Etch | | | Wet etch |
| Passivation Photo | | | Cobilt Aligner |
| Passivation Etch | | | Drytek RIE |

Figure 2